LA-UR-01-1122

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Submitted to: To be delivered at the Conference on Fractured Rocks March 26-28, 2001
Toronto,

Los Alamos
NATIONAL LABORATORY

OBSERVATION AND ANALYSIS OF A PRONOUNCED PERMEABILITY AND POROSITY SCALE-EFFECT IN UNSATURATED FRACTURED TUFF

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INTRODUCTION

Over 270 single-hole (Guzman et al., 1996) and 44 cross-hole pneumatic injection tests (Illman et al., 1998; Illman, 1999) have been conducted at the Apache Leap Research Site (ALRS) near Superior, Arizona. They have shown that the pneumatic pressure behavior of fractured tuff at the site is amenable to analysis by methods which treat the rock as a continuum on scales ranging from meters to tens of meters, and that this continuum is representative primarily of interconnected fractures. Both the single-hole and cross-hole test results are free of skin effect. Single-hole tests have yielded estimates of air permeability at various locations throughout the tested rock volume, on a nominal support scale of about 1 m. The corresponding log permeability data exhibit spatial behavior characteristic of a random fractal and yield a kriged estimate (Fig. 1) of how these 1-m scale log permeabilities vary in three-dimensional space (Chen et al., 2000).

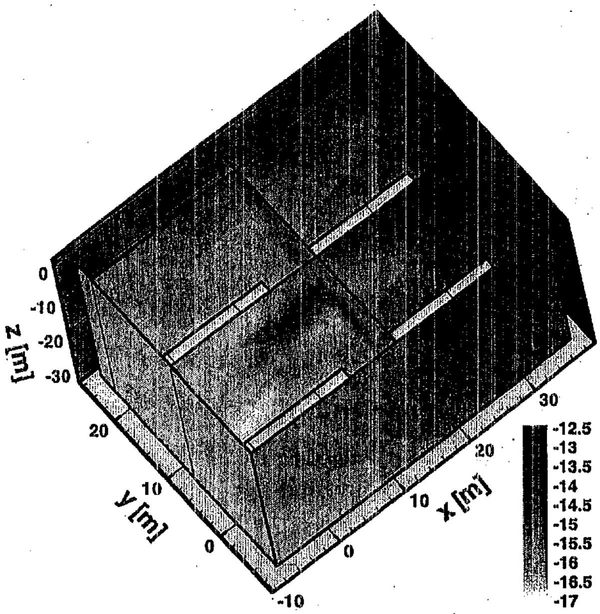

Figure 1. Three-dimensional representation of kriged $\log_{10}$-transformed air permeability obtained by geostatistical analysis of single-hole pneumatic test data (Chen et al., 2000).

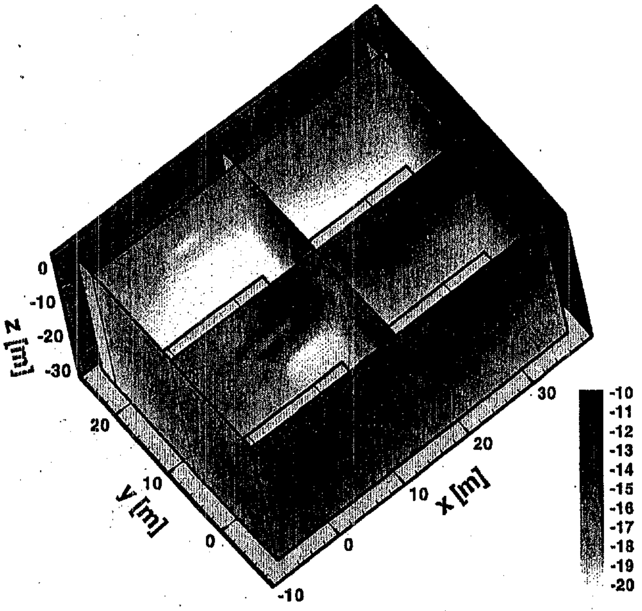

Figure 2. Three-dimensional representation of kriged $\log_{10}$-transformed air permeability obtained by simultaneous numerical inversion of cross-hole tests PP4, PP5, and PP6 (Vesselinov et al., 2000).

Cross-hole tests have been analyzed by means of a three-dimensional inverse model (Vesselinov et al., 2000) in two ways: (a) by interpreting pressure records from individual borehole monitoring intervals, one at a time, while treating the rock as if it was spatially uniform; and (b) by using the inverse model to interpret

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pressure records from multiple tests and borehole monitoring intervals simultaneously, while treating the rock as a random fractal characterized by a power variogram. The first approach has yielded equivalent air permeabilities and air-filled porosities for a rock volume characterized by a length-scale of several tens of meters. Comparable results have been obtained by means of type-curves (Illman and Neuman, 2001). The second approach amounts to three-dimensional pneumatic tomography, or stochastic imaging, of the rock. It has yielded a high-resolution geostatistical estimate of how air permeability and air-filled porosity, defined over grid blocks having a length-scale of 1 m, vary throughout the modeled rock volume (Fig.2). These tomographic images are comparable to those obtained by the kriging of 1-m scale log permeability data from single-hole tests (Fig. 1). The results reveal a highly pronounced scale effect in permeability and porosity at the ALRS. We analyze the scaling of permeability at the site on the basis of a recent theory, which is consistent with our representation of the rock as a random fractal.

ILLUSTRATION OF SCALE-EFFECT

To illustrate the scale effect, we consider the analysis of pressure variations with time in various packer-isolated borehole intervals during five cross-hole tests labelled PP4 – 8. The average of $\log_{10}k$ estimates (k being air permeability) obtained upon inverting these data numerically, while treating k and the air-filled porosity ϕ of the rock as if they were uniform, is - 13.7. The average of $\log_{10}k$ estimates obtained upon analysing pressure records from cross-hole test PP4 (Fig. 3) using type-curves, which likewise consider k and ϕ to be uniform, is - 13.5. The numerical inverse and type curve average estimates are thus virtually identical.

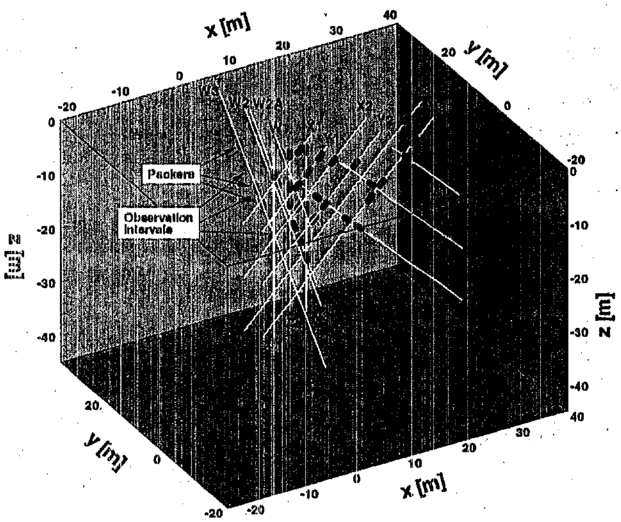

Figure 3. Boreholes, packers and computational region for test PP4 (Vesselinov et al., 2000).

On the other hand, the spatial average of $\log_{10}k$ estimates obtained upon inverting pressure data from tests PP4 – 6 numerically, while treating k and ϕ as random fields characterised by power variograms, is - 15.7. The spatial average of kriged $\log_{10}k$ estimates obtained from single-hole test data is - 15.2. The spatially averaged estimates obtained from cross-hole and single-hole test interpretations, while treating the rock as being randomly nonuniform, are thus very similar. However, the average numerical inverse estimate of k obtained by treating the rock as being spatially uniform is seen (in this illustration) to be exactly 100 times larger than that obtained by treating the rock as being spatially nonuniform.

The average of $\log_{10}\phi$ estimates obtained upon inverting PP4 - 8 data numerically, while treating k and ϕ as if they were uniform, is - 1.6. The average of $\log_{10}\phi$ estimates obtained upon analysing pressure records from cross-hole test PP4 using type-curves, which likewise consider k and ϕ to be uniform, is - 2.1. Both values are considerably higher than the spatial average of $\log_{10}\phi$ estimates, - 3.0, obtained upon inverting pressure data from tests PP4 – 6 numerically, while treating k and ϕ as random fields characterised by power variograms. In particular, the average numerical inverse estimate of ϕ obtained by treating the rock as being spatially uniform is 25 times larger than that obtained by treating the rock as being spatially nonuniform.

Consistency between cross-hole and single test results suggests that these pronounced permeability and porosity scale effects are unrelated to the method of testing. Consistency between numerical and type curve interpretations of the cross-hole pressure data under the assumption of rock uniformity, and between numerical inverse cross-hole k estimates and steady-state single-hole k estimates under the assumption of rock nonuniformity, implies that the scale effect is unrelated to the method of test interpretation. Considering additionally that our results are not affected by virtually any skin effect, there is no escaping the conclusion that the observed permeability and porosity scale effects at the ALRS are real.

ANALYSIS OF SCALE-EFFECT

The single-hole $\log_{10}k$ data fit a power variogram $\gamma(s)=C_o s^{2H}$ with Hurst coefficient H given by $2H$ = 0.45. These data are thus representative of a nonstationary random field with stationary increments (a fractal).

In our numerical inverse analysis of the cross-hole tests we used $\gamma(s)=C_o s^{2H}$ to characterise the spatial variability of $\log_{10}k$. We found that the best estimate of the Hurst coefficient was given by $2H \approx 0.75$.

It is possible to fit the single-hole $\log_{10}k$ data to a truncated power variogram $\gamma(s/\lambda_l)=\sigma_l^2 f(H,s/\lambda_l)$ with variance $\sigma_l^2 = C_o\lambda_l^{2H}/\Gamma(1-H)(\pi/4)^H$ (Di Federico and Neuman, 1997) by setting the coefficient to C_o = 0.22, the Hurst coefficient to $2H$ = 0.75, the variance to $\sigma_{l\text{-}SH}^2$ = 0.87, and the cut-off scale to $\lambda_{l\text{-}SH}$ = 9 m. According to the theory of Di Federico and Neuman, the same variogram should apply on the scale of the cross-hole tests but with different values of the variance $\sigma_{l\text{-}CH}^2$ and the cut-off scale $\lambda_{l\text{-}CH}$. The latter is related to the characteristic length scale of the cross-hole test domain, $L_{l\text{-}CH}$, via $\lambda_{l\text{-}CH}=\mu L_{l\text{-}CH}$ where μ is a coefficient. We evaluate $\sigma_{l\text{-}CH}^2$, $\lambda_{l\text{-}CH}$ and μ jointly for $2H$ = 0.75 by iterating between $\lambda_{l\text{-}CH}=\mu L_{l\text{-}CH}$; the upscaling formula (Di Federico et al., 1999)

$$\frac{k_{eq\text{-}CH}}{k_{g\text{-}CH}} = \exp\left\{\sigma_{l\text{-}CH}^2\left[\frac{1}{2}-D_{st}(H,\mu)\right]\right\} \tag{1}$$

where we set the equivalent conductivity $k_{eq\text{-}CH}$ equal to the geometric mean of uniform inverse estimates, and the geometric mean conductivity $k_{g\text{-}CH}$ equal to the geometric mean of spatially varying inverse estimates; and

$$\sigma_{l\text{-}CH}^2 = C_o\lambda_{l\text{-}CH}^{2H}/\Gamma(1-H)(\pi/4)^H. \tag{2}$$

To illustrate, we set $\log_{10}k_{eq\text{-}CH}$ = - 13.57 (based on numerical inversion of cross-hole test *PP4* upon treating the rock as being uniform), $\log_{10}k_{g\text{-}CH}$ = - 15.23 (based on numerical inversion of the same test upon treating the rock as being nonuniform while parameterizing it with the aid of 32 pilot points), and $L_{l\text{-}CH}$ = 54.1 *m* (the geometric mean dimension of a rectangle within which we conduct our cross-hole numerical test analysis). This yields $\sigma_{l\text{-}CH}^2$ = 2.11, which is somewhat larger than the variance σ_{CH}^2 = 1.67 of the nonuniform numerical inverse estimates. These two values are mutually consistent considering that $\sigma_{l\text{-}CH}^2$ represents the variance of the actual random $\log_{10}k$ field, whereas σ_{CH}^2 represents the spatial variance of its smooth estimate.

The analysis further yields $\lambda_{l\text{-}CH} = 29.13\ m$. This and $\sigma^2_{l\text{-}CH} = 2.11$ are perfectly consistent with the single-hole statistics $\sigma^2_{l\text{-}SH} = 0.87$ and $\lambda_{l\text{-}SH} = 9\ m$, considering that the two sets satisfy exactly the theoretical scaling relationship $\sigma^2_{SH} / \sigma^2_{CH} = \lambda^{2H}_{l\text{-}SH} / \lambda^{2H}_{l\text{-}CH}$ implied by (2). We further find from our analysis that $\mu = 0.54$, which is somewhat larger than (but not inconsistent with) the value of $\mu = 0.35$ we have previously established based on the single hole test data.

CONCLUSIONS

1. There is a very pronounced scale effect in air permeability and air-filled porosity at the ALRS. As there is consistency between single-hole and cross-hole test results, the scale effect is unrelated to the method of testing. As there is consistency between results obtained by means of diverse steady-state and transient, analytical and numerical methods of test interpretation, the scale effect is unrelated to the method of interpretation. As neither the single-hole nor the cross-hole test results have been affected by any skin effect of consequence, the scale effect is unrelated to skin phenomena. The observed scale effect at the ALRS appears to be real.
2. The observed permeability scale effect at the ALRS is amenable to analysis by, and consistent with, a recent scaling theory (Di Federico and Neuman, 1997; Di Federico et al., 1999) that views log permeability as a truncated random fractal with cut-off scales proportional to the support and window scales of the available data.

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